Project X Physics Study, Fermilab, June 21 2012

Kaon Physics WG - Theory

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Contributions: Joachim Brod, Uli Haisch, Wolfgang Altmannshofer, Philippe Mertens, Stefania Gori

Outline

- Intensity frontier and Kaon physics
- SM predictions for “rare” K decays
- BSM
  - Model-independent considerations
  - Models (SUSY, RS, light sector)
- K decays at ORKA + Project X
  - theory homework

Intensity Frontier and Kaons

- Goal (see Y. Grossman's talk): reconstruct the "New SM" dynamics

We know it's there at some level

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

Eventually want to get its structure and parameters

- Both Energy and Intensity Frontier needed:

Energy Frontier
(direct access to new d.o.f)

- EWSB mechanism
- Discover new particles
- …

Intensity Frontier
(indirect access to new d.o.f through virtual effects)

- CP violation (w/o flavor)
- Flavor symmetries (quarks, leptons)
- L and B violation
- ....

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- CP violation (w/o flavor)
- Flavor symmetries (quarks, leptons)
- L and B violation
- ....

- Kaons: central in understanding the (non-generic) flavor sector of $\mathcal{L}_{BSM}$

- One observable: if clean enough, "discovery" potential ($O_{exp} \neq O_{SM}$)
  - might reveal new source of symmetry violation (CP, ...)
  - no handle on underlying dynamics (multiple explanations)
- More observables (+ LHC): model discriminating power!
  - info on underlying (flavor) dynamics
  - if model is known (LHC?), disentangle parameters

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$$\Downarrow$$

Points to the need to build a "research program":

- flagship measurements characterized by high discovery potential
- along the way measure all possible K modes: discriminating power

Project X can play a major role in this!

Flavor physics and K decays

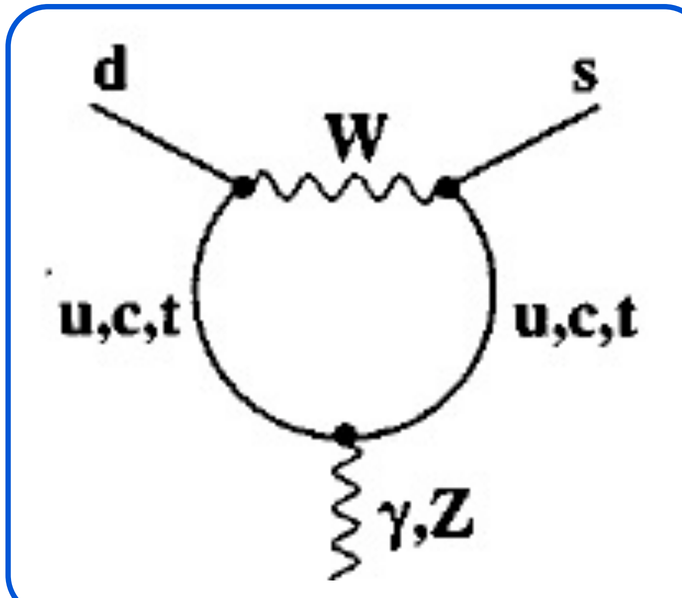
- SM: very specific pattern of loop-induced $\Delta F=1$ and $\Delta F=2$ FCNC (GIM mechanism and CKM hierarchy)

Flavor physics and K decays

- SM: very specific pattern of loop-induced ΔF=1 and ΔF=2 FCNC (GIM mechanism and CKM hierarchy)

- Rare K decays are deep probe of new flavor-breaking structures

$$\boxed{d_i \;\to\; d_j \;(\gamma,\; \ell^+\ell^-,\; \nu\bar{\nu})}$$



- No SM tree-level contribution

- Strong suppression from λ^5 CKM factor (enhanced sensitivity to BSM effect)

- Predicted with high precision (if "short-distance" dominated)

$$\boxed{A(s \to d)_{\mathrm{S.D.}} \sim \frac{C_{\mathrm{SM}}}{16\pi^2 M_W^2}\, y_t^2\, V_{ts}\, V_{td}^* \;+\; \frac{C_{\mathrm{new}}}{\Lambda^2}\, \delta_{sd}}$$

Flavor physics and K decays

- SM: very specific pattern of loop-induced $\Delta F=1$ and $\Delta F=2$ FCNC

- Golden modes ($K \to \pi\nu\nu$) provide a win-win opportunity

- Expect sizable [O(1)] NP effects (no λ^5 suppression)

- Even if BSM effect is "small" (MFV, ...) can still detect it due to theoretically clean SM "background"

- But there is more than golden modes (see later)

(if "short-distance" dominated)

$$A(s \to d)_{\rm S.D.} \sim \frac{C_{\rm SM}}{16\pi^2 M_W^2}\, y_t^2\, V_{ts} V_{td}^* + \frac{C_{\rm new}}{\Lambda^2}\, \delta_{sd}$$

Rare K decays in the SM

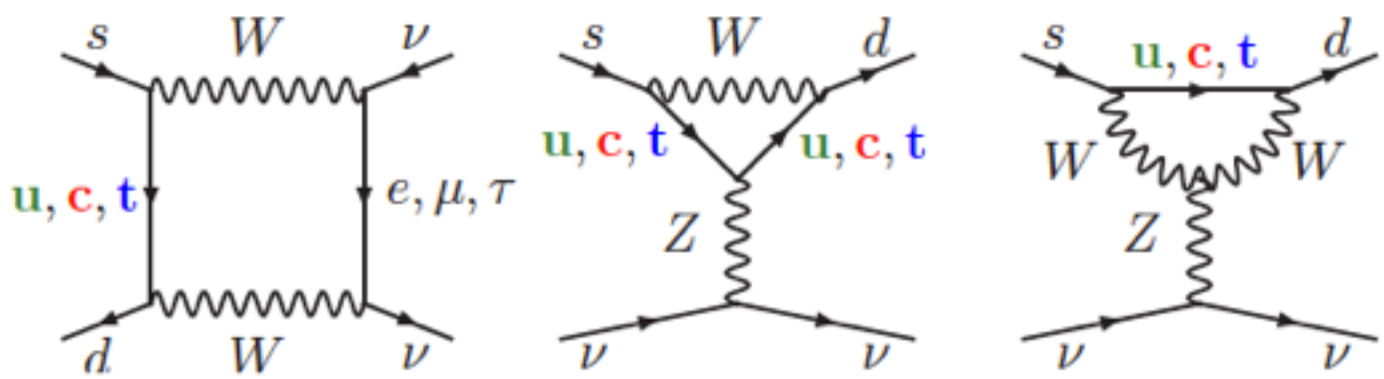
Joachim Brod
Philippe Mertens

- WG focused on the four cleanest modes

$K^+ \to \pi^+ \nu\nu$ $\quad K_L \to \pi^0 \nu\nu$ $\quad K_L \to \pi^0 e^+e^-$ $\quad K_L \to \pi^0 \mu^+\mu^-$

- Clean short distance amplitude
- Sensitivity to different BSM operators
- Various degrees of "long distance" contamination
  - Small in $K \to \pi\nu\nu$ (negligible in K_L mode)
  - Sizable l.d. EM contaminations in $K \to \pi ee$, $\pi\mu\mu$, but controllable with input from other decays

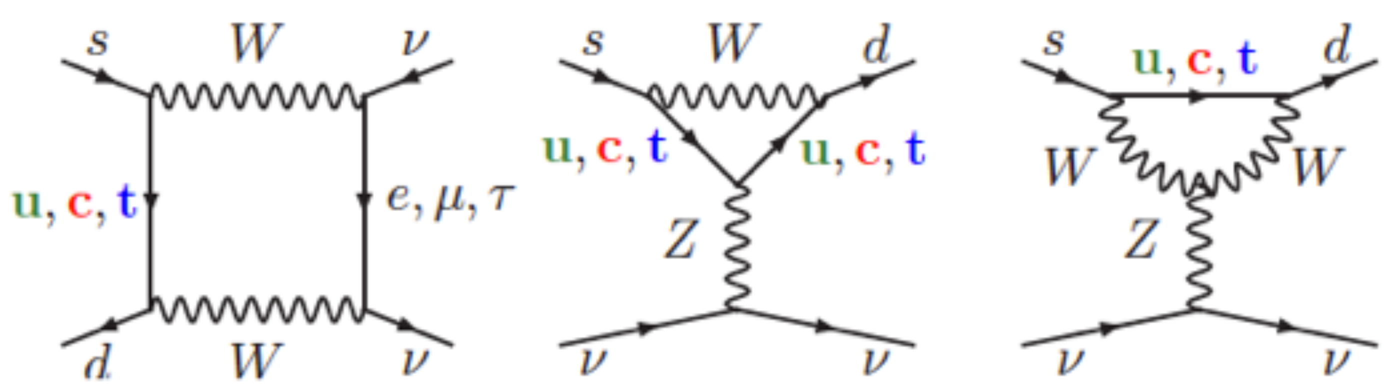
Neutrino modes



- Why are we able to make precise predictions?
  - Short-distance (SD) contributions (Wilson coefficients) can be calculated precisely in perturbation theory
  - Semileptonic decays $\Rightarrow$ extract matrix elements via isospin symmetry from $K_{\ell 3}$ decays [Marciano, Parsa '96]
  - quadratic GIM suppresses long-distance (LD) contributions
  - Error mainly parametric – can be reduced in the future

Joachim Brod

Neutrino modes



$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im}\, X)^2$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) \propto |X|^2$$

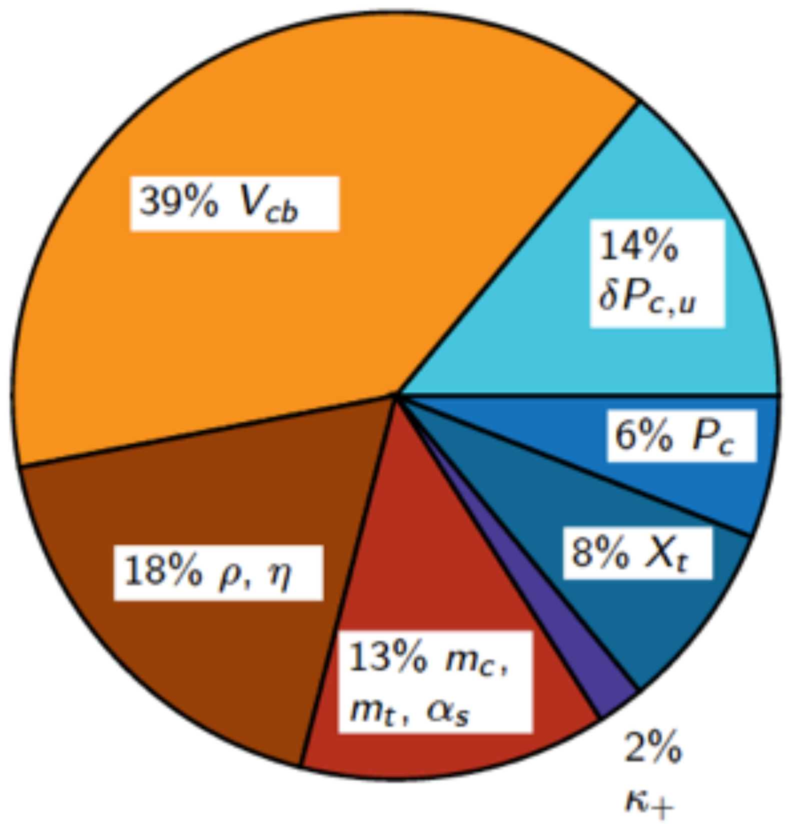
$$X = \frac{\lambda_t}{\lambda^5} X_t + \frac{\mathrm{Re}\lambda_c}{\lambda} P_{c,u}$$

$$\lambda_i = V_{is}^* V_{id}\,, \quad \lambda \approx 0.23\,, \quad X_t \approx 1.5\,, \quad P_{c,u} \approx 0.4$$

Uli Haisch

$K^+ \to \pi^+ \nu \bar{\nu}$: Error Budget

Joachim Brod

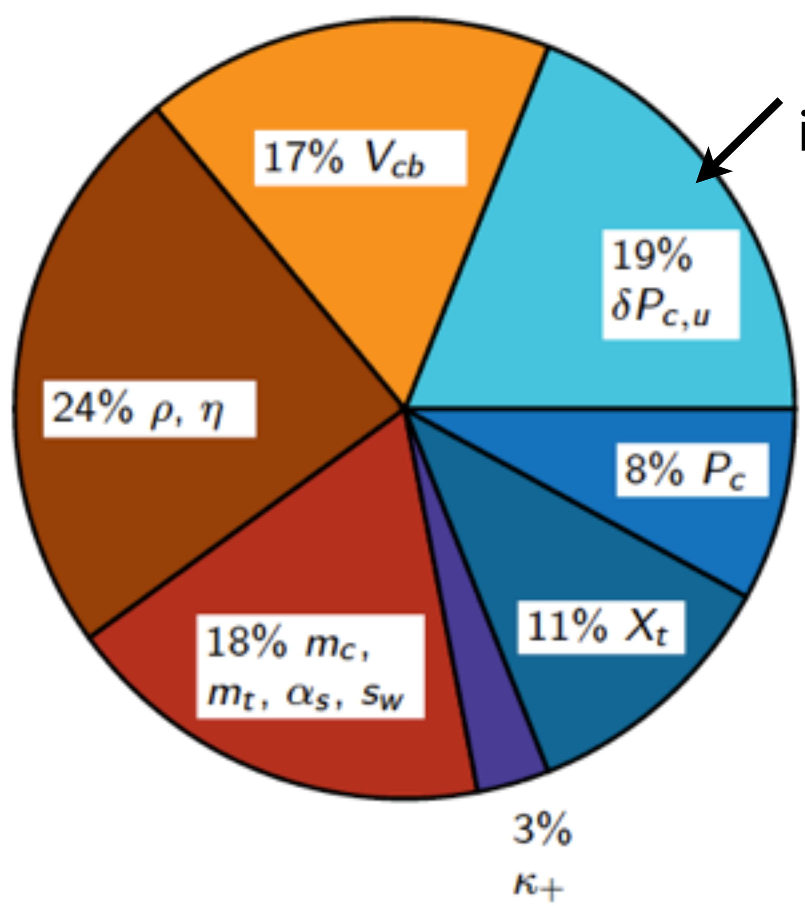


$$\mathrm{Br}^{\mathrm{th}}(K^+) = 7.81(75)(29) \times 10^{-11}$$

10%

$\delta V_{cb}/V_{cb} = 1\%$

Long distance contribution improvable with lattice QCD

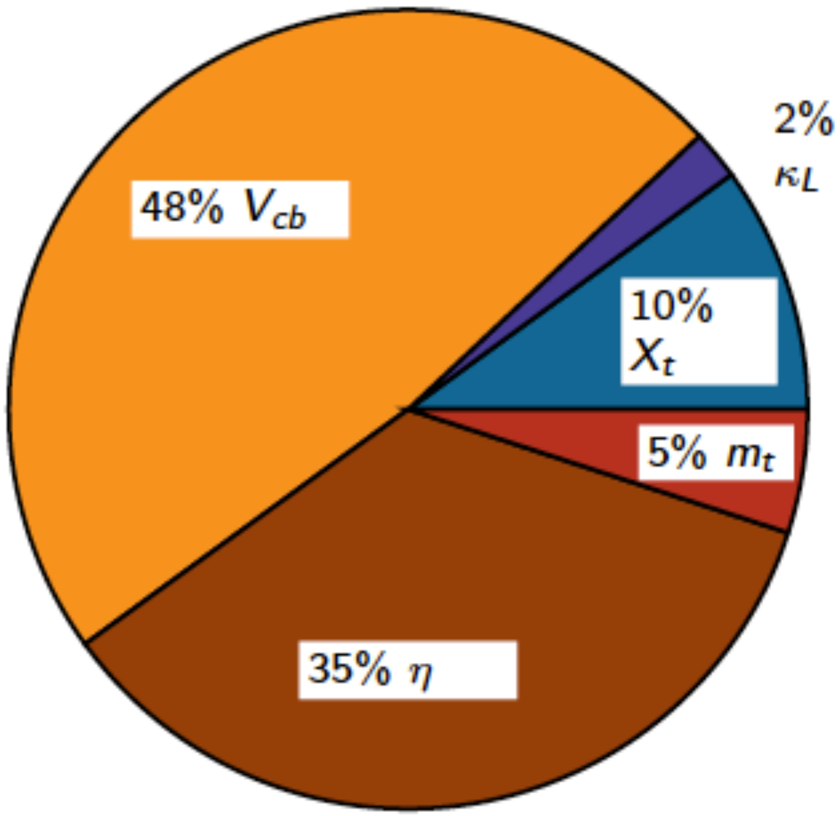


$$\mathrm{Br}^{\mathrm{th}}(K^+) = 7.81(37)(29) \times 10^{-11}$$

6%

$K_L \to \pi^0 \nu \bar{\nu}$: Error Budget

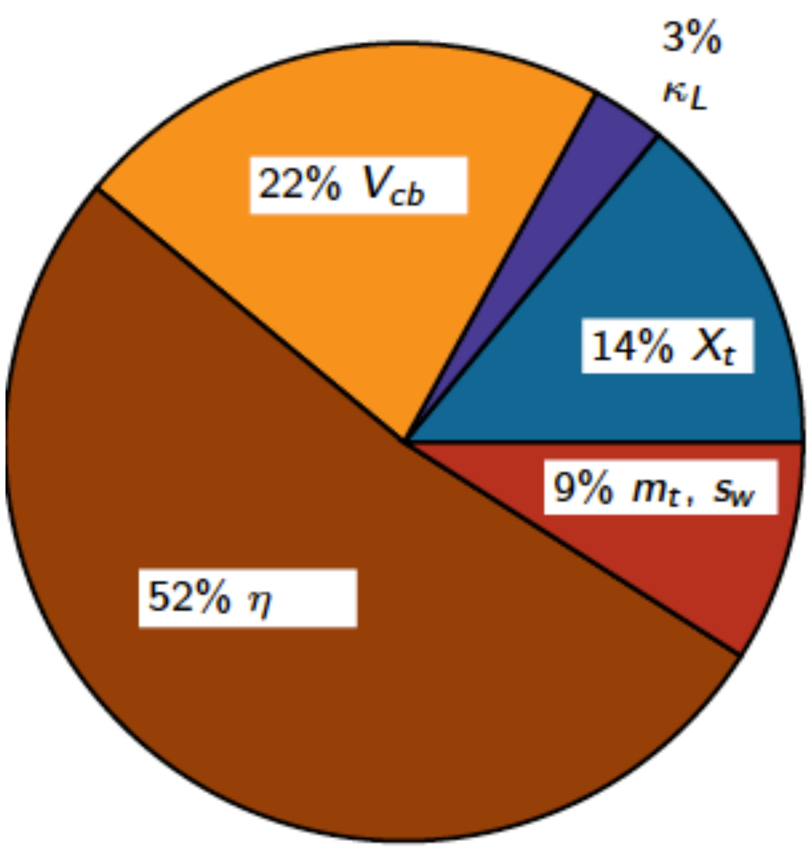
Joachim Brod



$$\mathrm{Br}^{\mathrm{th}}(K_L) = 2.43(39)(6) \times 10^{-11}$$

15%

$\delta V_{cb}/V_{cb} = 1\%$



$$\mathrm{Br}^{\mathrm{th}}(K_L) = 2.43(25)(6) \times 10^{-11}$$

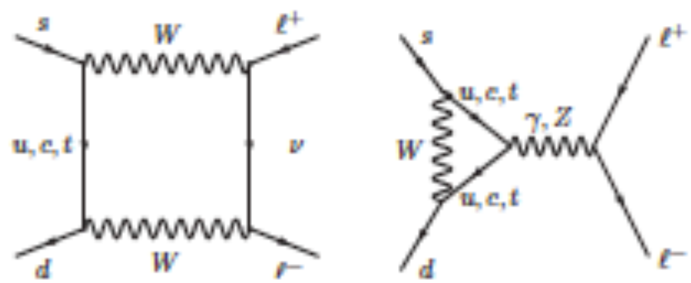
10%

Charged lepton modes

- Three contributions to $K_L \to \pi^0 \ell^+ \ell^-$

$$Q_{7V[A]} = (\bar{s}_L \gamma_\mu d_L)(\bar{\ell}\gamma^\mu[\gamma_5]\ell)$$

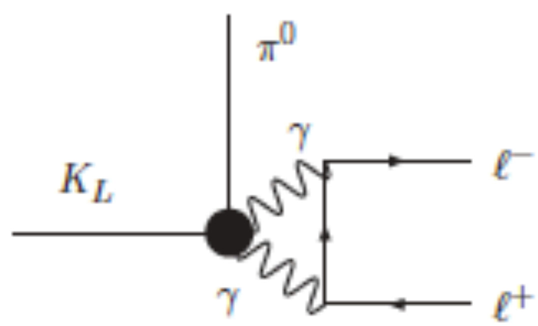
DCPV:



- NLO QCD (scale dependence $< 1.5\%$)

  [Buchalla et al. '95]

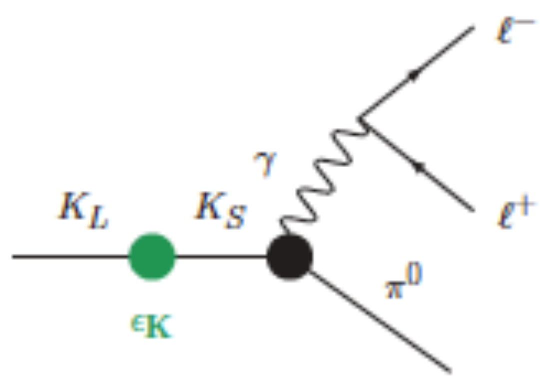
CPC:



- Estimate from $K_L \to \pi^0\gamma\gamma$

  [Isidori et al. '04]

ICPV:



- Estimate from ϵ_K, $K_S \to \pi^0 \ell^+ \ell^-$

  [D'Ambrosio et al. '98, Mescia et al. '06]

- Sign of interference with Q_{7V}?

  [Buchalla et al. '03, Friot et al. '04; Bruno et al. '93]

Joachim Brod

Charged lepton modes

- Three contributions to $K_L \to \pi^0 \ell^+ \ell^-$
- Branching ratios

[Mertens, Smith '11]

$$B^{\text{theo}}(K_L \to \pi^0 e^+ e^-) = 3.23\,^{+0.91}_{-0.79}\,[1.37\,^{+0.55}_{-0.43}] \times 10^{-11}$$

$$B^{\text{theo}}(K_L \to \pi^0 \mu^+ \mu^-) = 1.29\,^{+0.24}_{-0.23}\,[0.86\,^{+0.18}_{-0.17}] \times 10^{-11}$$

- Uncertainty dominated by $K_S \to \pi^0 ee$ measurement

Joachim Brod,
Philippe Mertens

Rare K decays beyond the SM

- Two ways to study new physics

Uli Haisch

Top-down approach:	Bottom-up approach:
o concrete model of new physics o predict observables & correlations directly o are smoking gun signals possible?	o what data can be obtained? o how is it parametrized efficiently? o what can be learned about model classes?

(BSM EFT)

$$\mathcal{L}_{\rm eff} = \sum_i C_i Q_i$$

SUSY: Wolfgang's talk
RS: Stefania's talk
Dark sector: Philippe's talk

Uli's talk

EFT approach: Kaon scoresheet

Uli Haisch,
S. Jaeger

$$\mathcal{L}_{\text{eff}} = \sum_i C_i Q_i$$

Operator	Observable	$K^+ \to \pi^+ \nu \bar{\nu}$	$K_L \to \pi^0 \nu \bar{\nu}$	$K_L \to \pi^0 l^+ l^-$	$K_L \to l^+ l^-$	$K^+ \to l^+ \nu$	$P_T(K^+ \to \pi^0 \mu^+ \nu)$	Δ_{CKM}	ϵ'/ϵ	ϵ_K	in MSSM?
$Q_{lq}^{(1)}$	$(\bar{D}_L \gamma_\mu S_L)(\bar{L}_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	✓
$Q_{lq}^{(3)}$	$(\bar{D}_L \gamma_\mu \sigma^i S_L)(\bar{L}_L \gamma^\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	—	—	✓
Q_{qe}	$(\bar{D}_L \gamma_\mu S_L)(\bar{l}_R \gamma^\mu l_R)$	—	—	✓	hs	hs	✓	✓	—	—	small
Q_{ld}	$(\bar{d}_R \gamma_\mu s_R)(\bar{L}_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	small
Q_{ed}	$(\bar{d}_R \gamma_\mu s_R)(\bar{l}_R \gamma^\mu l_R)$	—	—	✓	hs	—	—	—	—	—	small
Q_{lq}^{t}	$(\bar{u}_R S_L)(\bar{l}_R L_L)$	—	—	—	—	✓	✓	✓	—	—	tiny
$(Q_{lq}^{t})^\dagger$	$(\bar{u}_R \sigma_{\mu\nu} S_L)(\bar{l}_R \sigma^{\mu\nu} L_L)$	—	—	—	—	—	?	?	—	—	tiny
Q_{qde}	$(\bar{d}_R S_L)(\bar{L}_L l_R)$	—	—	✓	✓	—	—	—	—	—	tiny
$Q_{qde}^{\dagger}$	$(\bar{D}_L s_R)(\bar{l}_R L_L)$	—	—	✓	✓	✓	✓	✓	—	—	large $\tan\beta$
$Q_{\phi q}^{(1)}$	$(\bar{D}_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	✓
$Q_{\phi q}^{(3)}$	$(\bar{D}_L \gamma_\mu \sigma^i S_L)(\phi^\dagger D^\mu \sigma^i \phi)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$Q_{\phi d}$	$(\bar{d}_R \gamma_\mu s_R)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	large $\tan\beta$ (non-MFV)

- In this framework, can study both
    - "discovery potential" of rare decays (constraints from other observables): how large of an effect can we expect?
    - "discriminating power" (correlations among various observables)

- Focus on Z-penguins (operators involving Higgs field):
    - most interesting since they contribute to ε'/ε
    - largest contribution in most models

Uli Haisch

Z penguins

- Left- and Right-handed Z penguins, modify FC Z-boson vertices

$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar d_L \gamma_\mu s_L Z^\mu + \widetilde C_{\rm NP}\, \bar d_R \gamma_\mu s_R Z^\mu$$

$C_{SM} \approx 0.8$

- Rare decay BRs with non-standard Z penguins

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar\nu) \propto (\mathrm{Im}\, X)^2$$

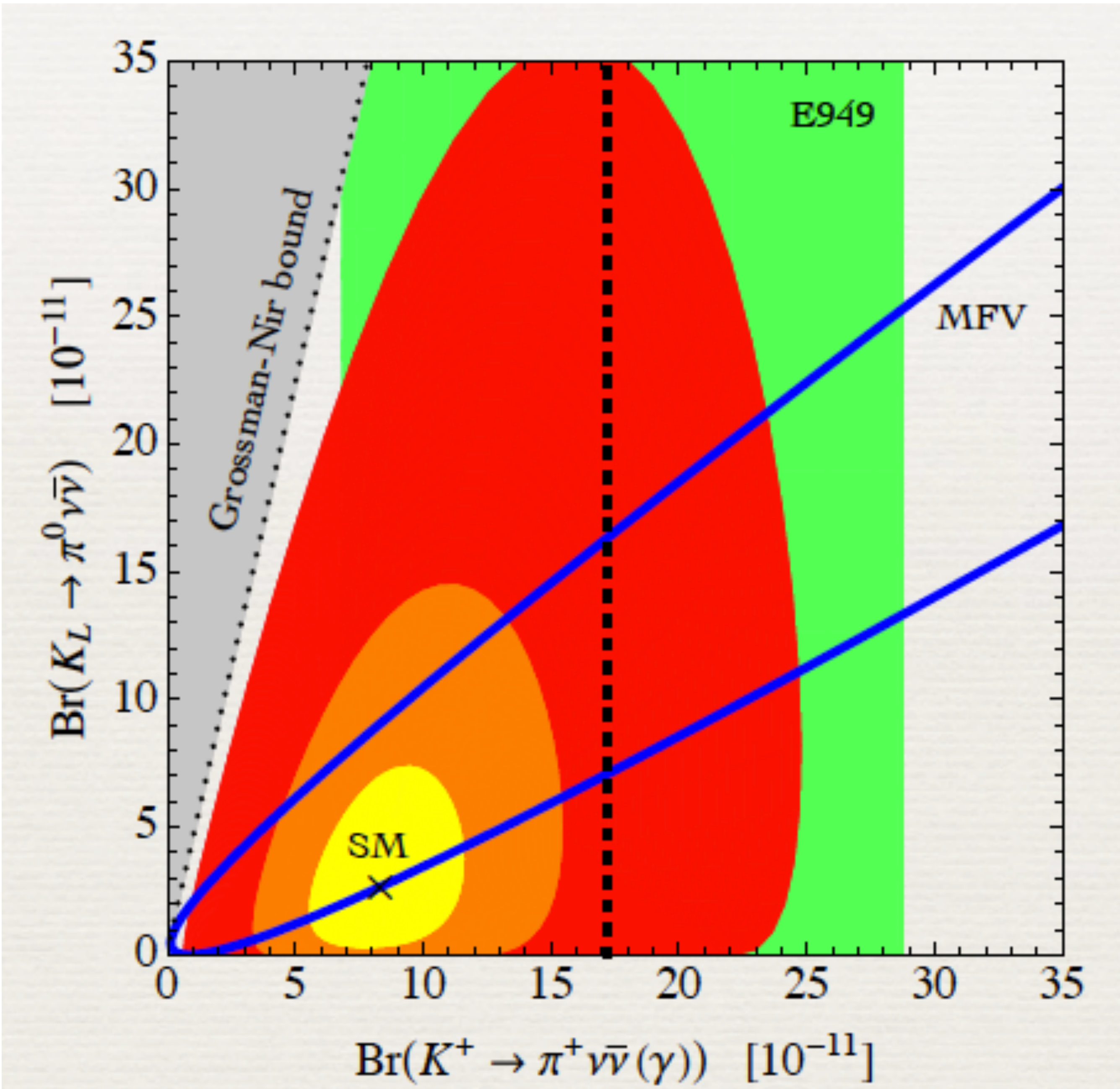
$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar\nu(\gamma)) \propto |X|^2$$

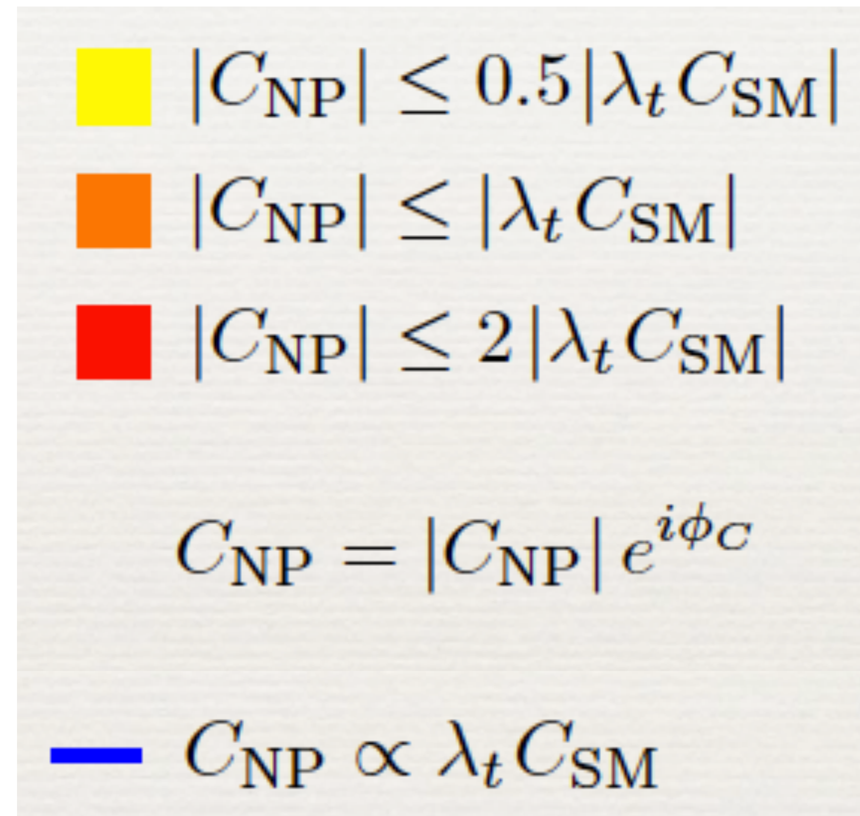
$$X = \frac{\lambda_t}{\lambda^5} X_t + \frac{\mathrm{Re}\lambda_c}{\lambda} P_{c,u} + \frac{1}{\lambda^5}\left(C_{\rm NP} + \widetilde C_{\rm NP}\right)$$

$$\lambda_i = V_{is}^* V_{id}\,, \quad \lambda \approx 0.23\,, \quad X_t \approx 1.5\,, \quad P_{c,u} \approx 0.4$$

Uli Haisch

Correlations in K→πνν modes



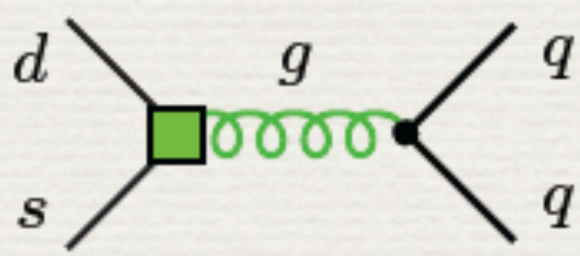


- Large (order-of-magnitude) effects allowed, but ...

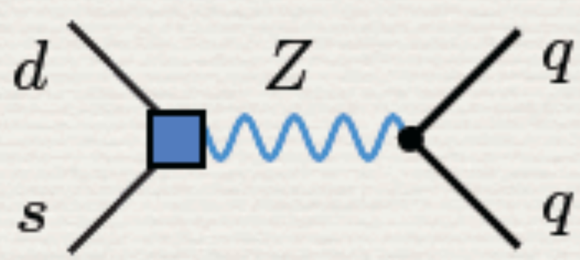
Anatomy of ε′/ε

- Prediction for ε′/ε very sensitive to interplay between QCD (Q_6) & electroweak (Q_8) penguin operators:

$$\frac{\epsilon'}{\epsilon} \propto -\mathrm{Im}\Big[\lambda_t\,(-1.4 + 13.8\,R_6 - 6.6\,R_8)$$
$$+\,(1.5 + 0.1\,R_6 - 13.3\,R_8)\,\Big(C_{\rm NP} - \widetilde{C}_{\rm NP}\Big)\Big]$$



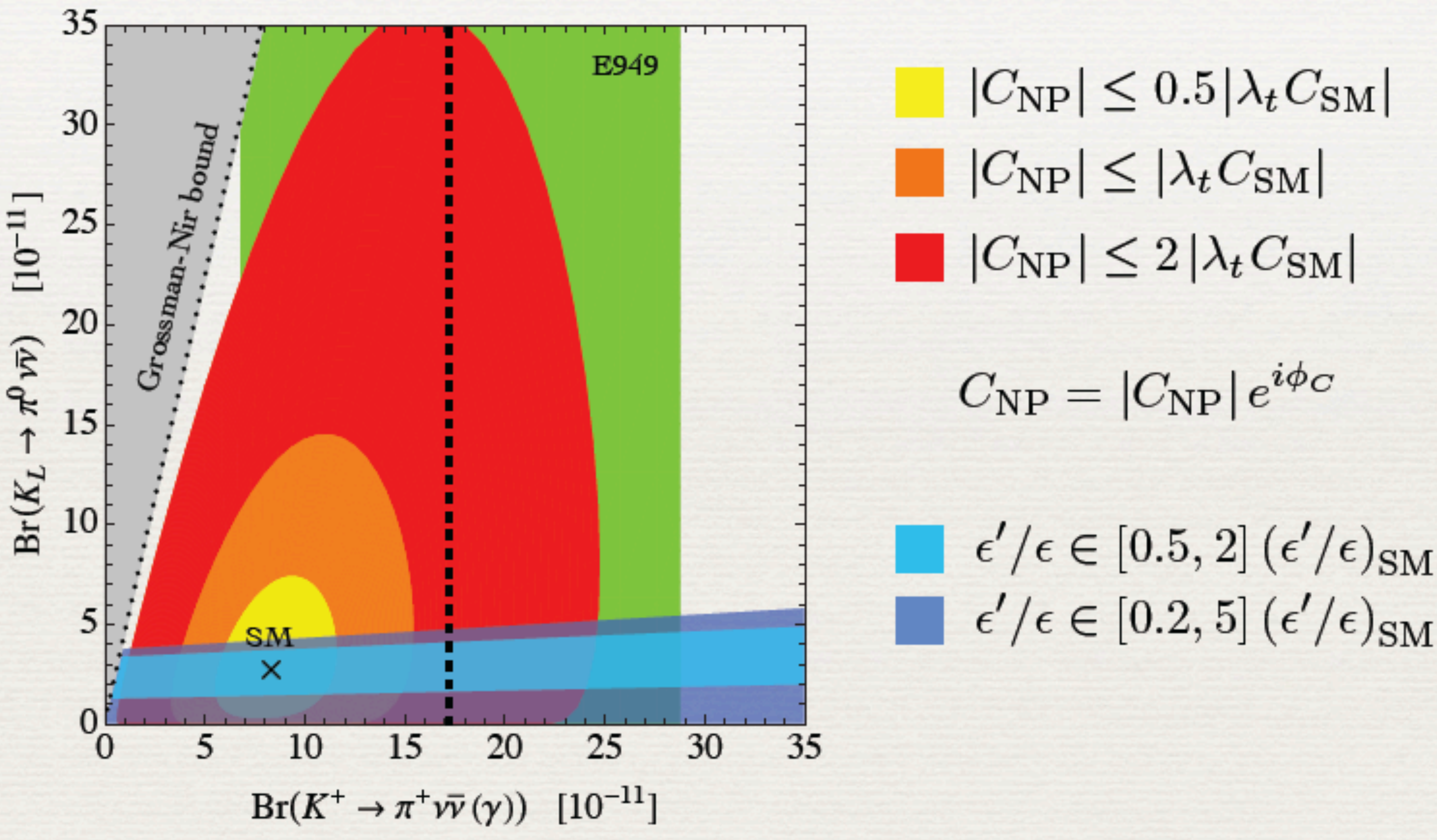
$\Rightarrow$ $R_6 \propto \langle (\pi\pi)_{I=0} | Q_6 | K \rangle \underset{\sim}{\in} [0.8, 2.0]$



$\Rightarrow$ $R_8 \propto \langle (\pi\pi)_{I=2} | Q_8 | K \rangle \underset{\sim}{\in} [0.8, 1.2]$

ε′/ε Strikes Back

Uli Haisch

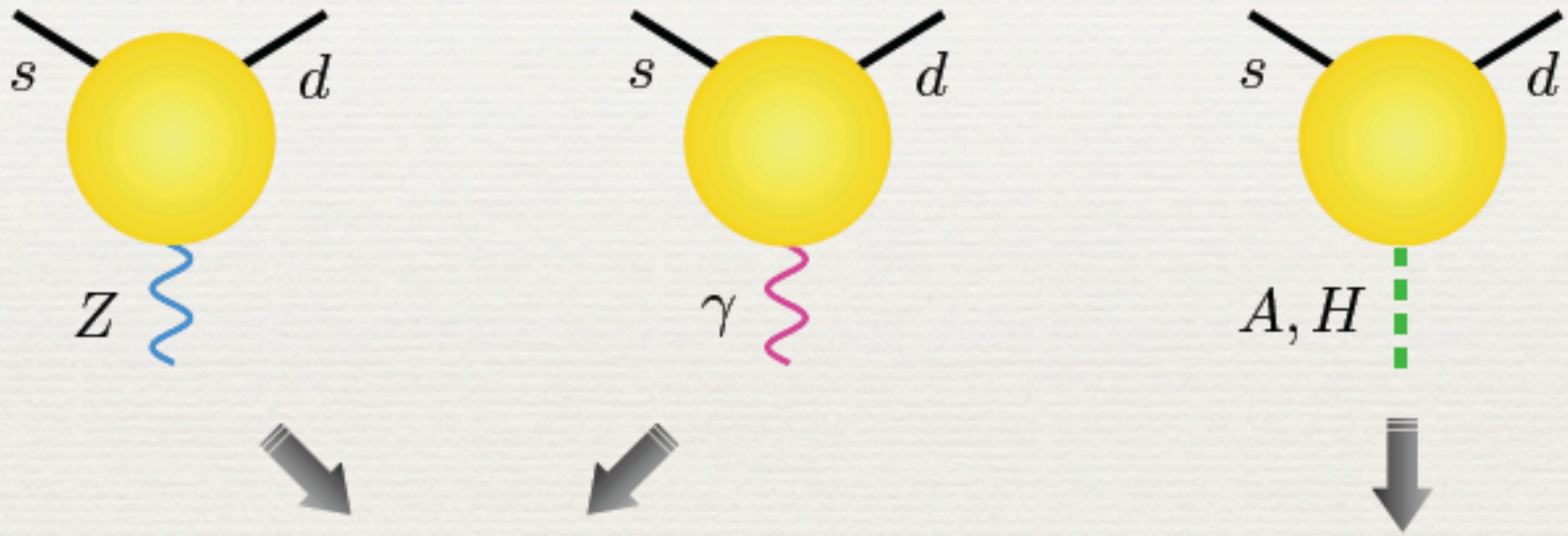


- Stringent correlation between ε’ and $K_L \to \pi^0\nu\nu$: ~50% deviations from SM BR still possible
- Correlation present in MSSM, RS, compositeness, ...

Uli Haisch

Anatomy of Leptonic Modes

- $K_L \to \pi^0 l^+ l^-$ modes receive contributions from (axial-) vector (A, V), (pseudo-)scalar (P, S), ... operators:



$$Q_V = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu l)$$

$$Q_A = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu \gamma_5 l)$$

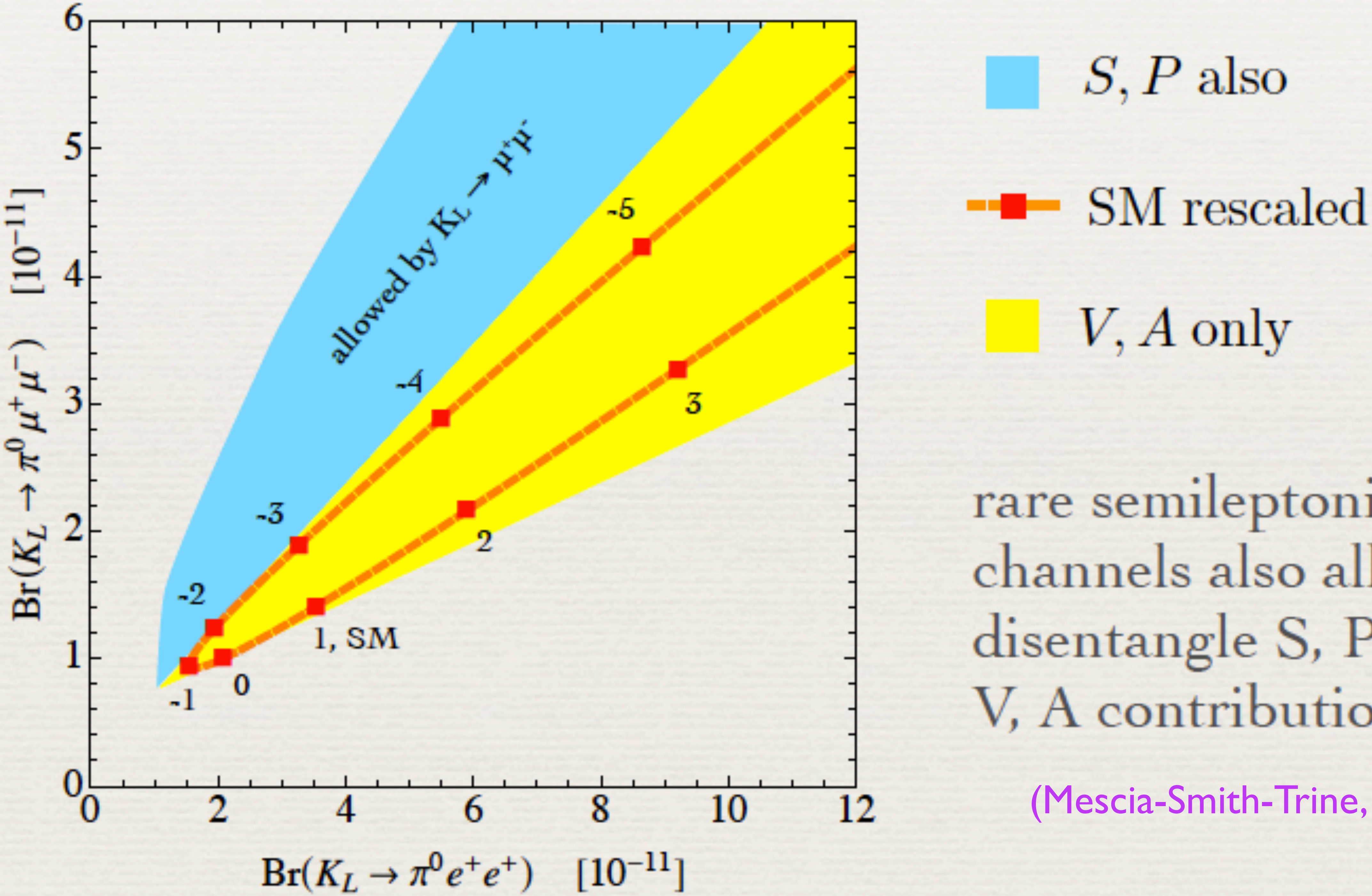
$$Q_S = (\bar{d}s)(\bar{l}l)$$

$$Q_P = (\bar{d}s)(\bar{l}\gamma_5 l)$$

[for further details see Joachim's & Phillipe's talks]

Uli Haisch

Correlations of Leptonic Modes



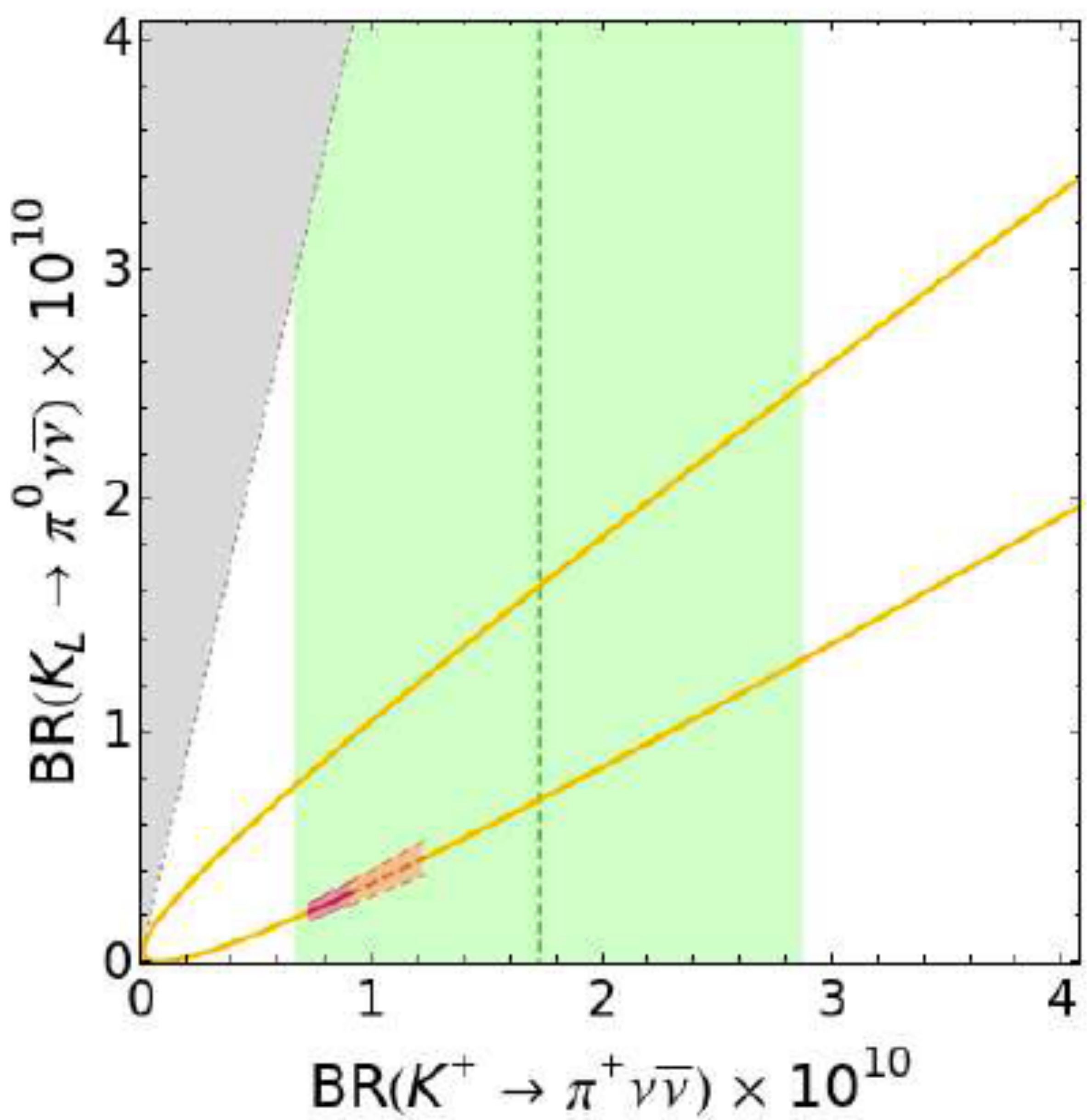
rare semileptonic kaon channels also allow to disentangle S, P from V, A contributions

(Mescia-Smith-Trine, ...)

Rare K decays in SUSY

Wolfgang Altmannshofer

- In the MSSM with MFV, the $K \to \pi\nu\bar{\nu}$ decays remain to a large extent SM-like. Visible deviations might come from a extended Higgs sector and are highly correlated between $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

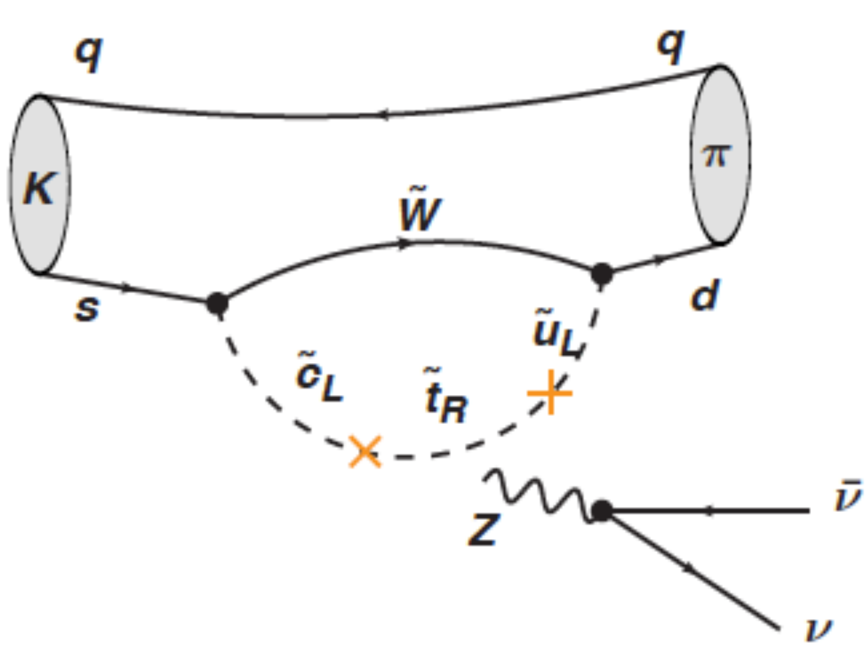


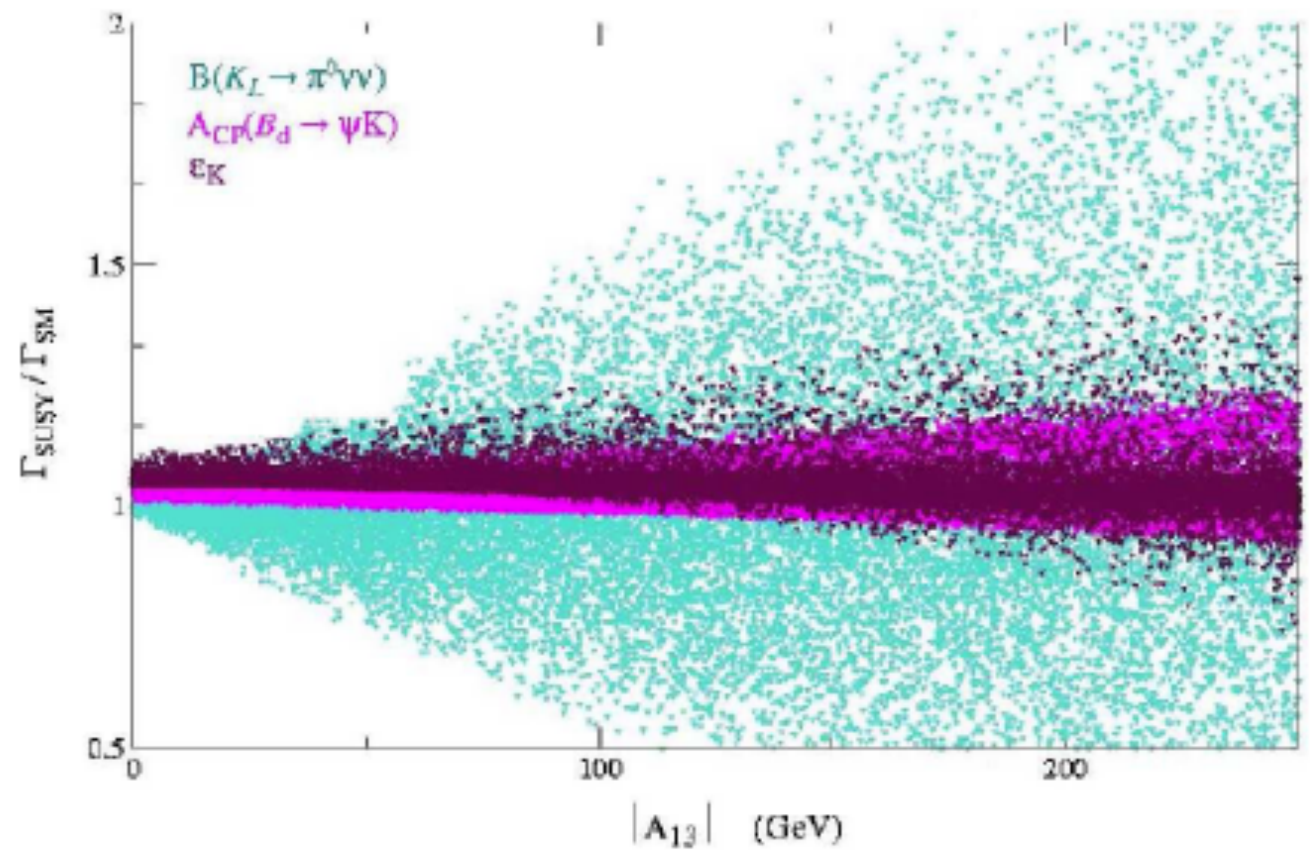
model independent MFV framework

MSSM with MFV

MSSM with MFV + extended Higgs sector

- In the MSSM beyond MFV, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ can be modified independently and are unique probes of flavor violation in the up-squark sector. Several motivated frameworks exist that lead to O(1) modifications of the branching ratios





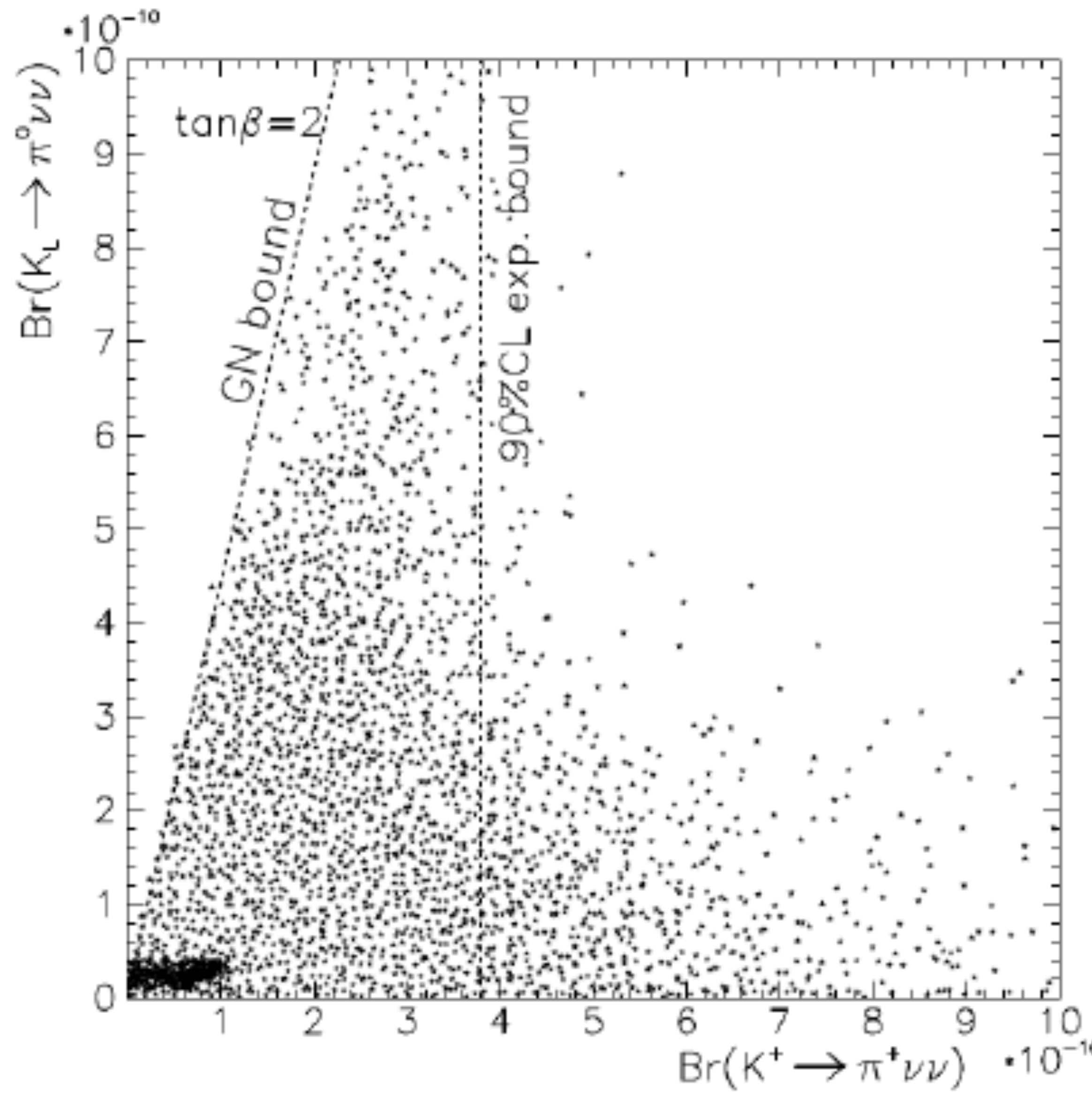
Isidori, Mescia, Paradisi, Smith, Trine, JHEP 0608(2006)

- In the MSSM beyond MFV,
  $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ can be modified independently and are unique probes of flavor violation in the up-squark sector.
  Several motivated frameworks exist that lead to O(1) modifications of the branching ratios

- result of a general scan of the MSSM parameter space, taking into account all relevant constraints (apart from ϵ'/ϵ !):

  both branching ratios can be enhanced by more than an order of magnitude (corresponding regions of parameter space are to a certain amount fine-tuned)

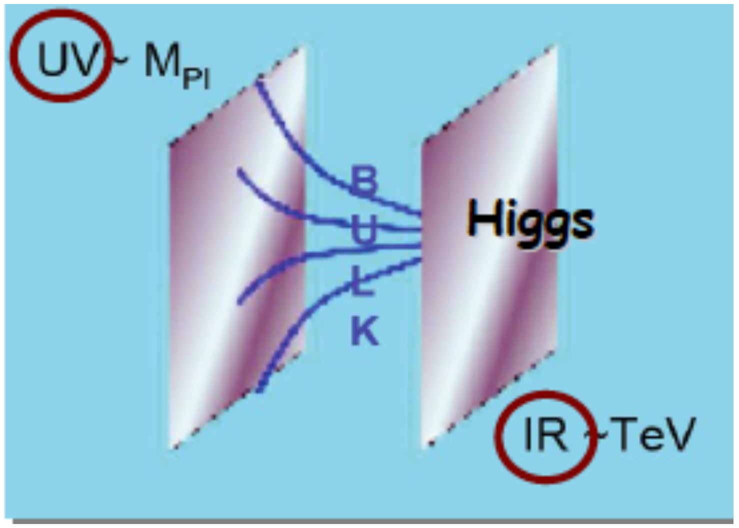
  exp. results already give non-trivial constraints on the MSSM parameter space



Buras, Ewerth, Jager, Rosiek,
Nucl. Phys. B714 (2005)

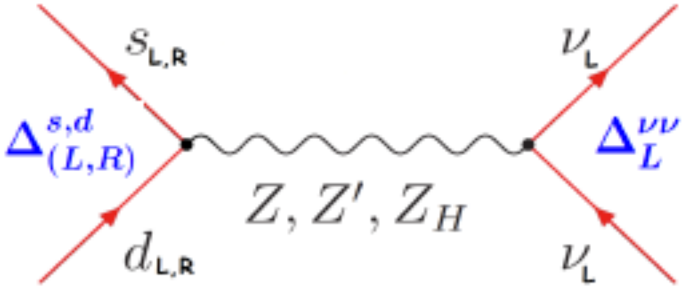
Stefania Gori

Rare K decays in warped extra dims

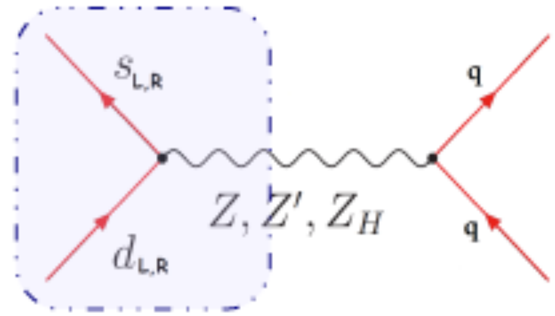


- Sources of flavor violation: 5D Yukawa couplings and fermionic "bulk" mass parameters

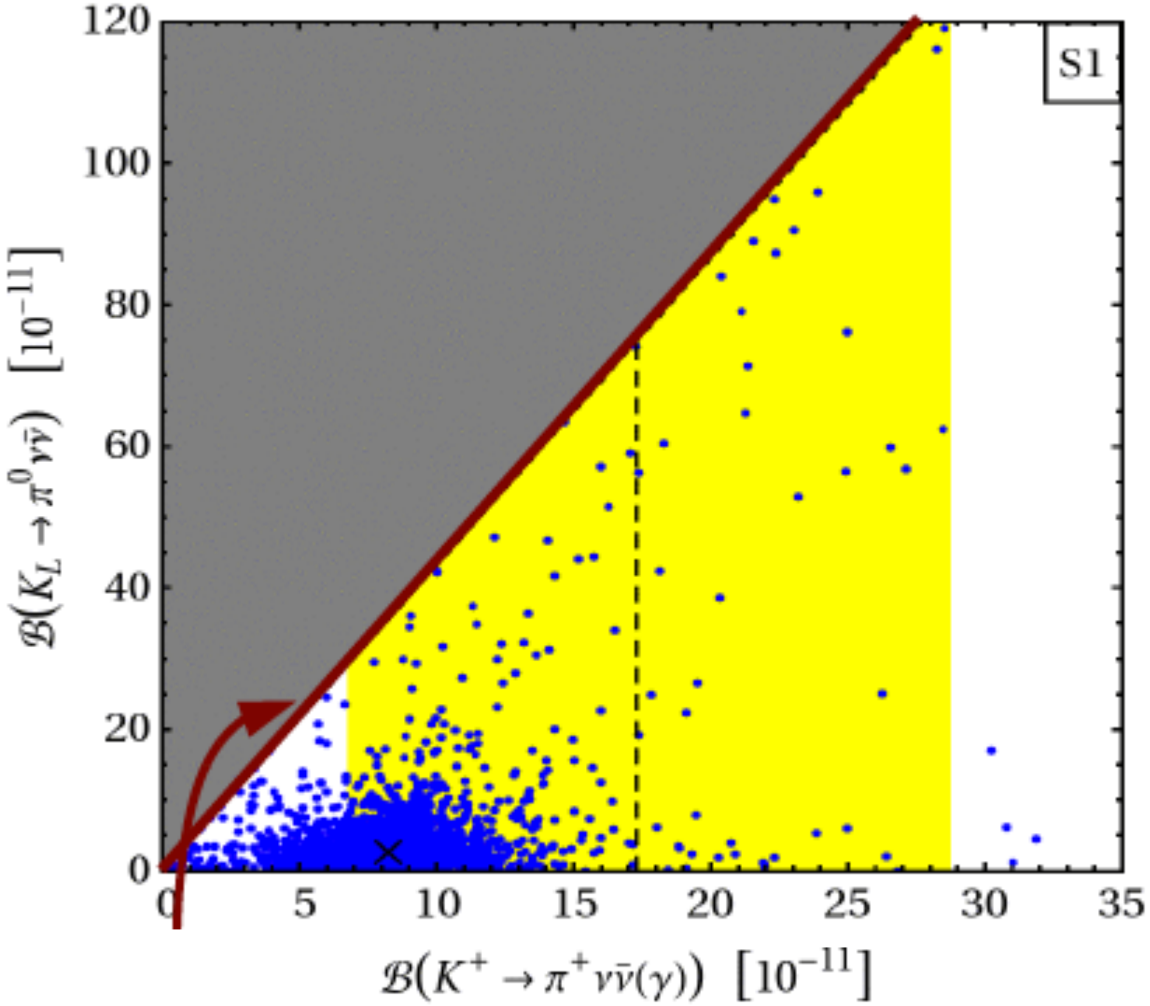
- Tree-level FCNCs



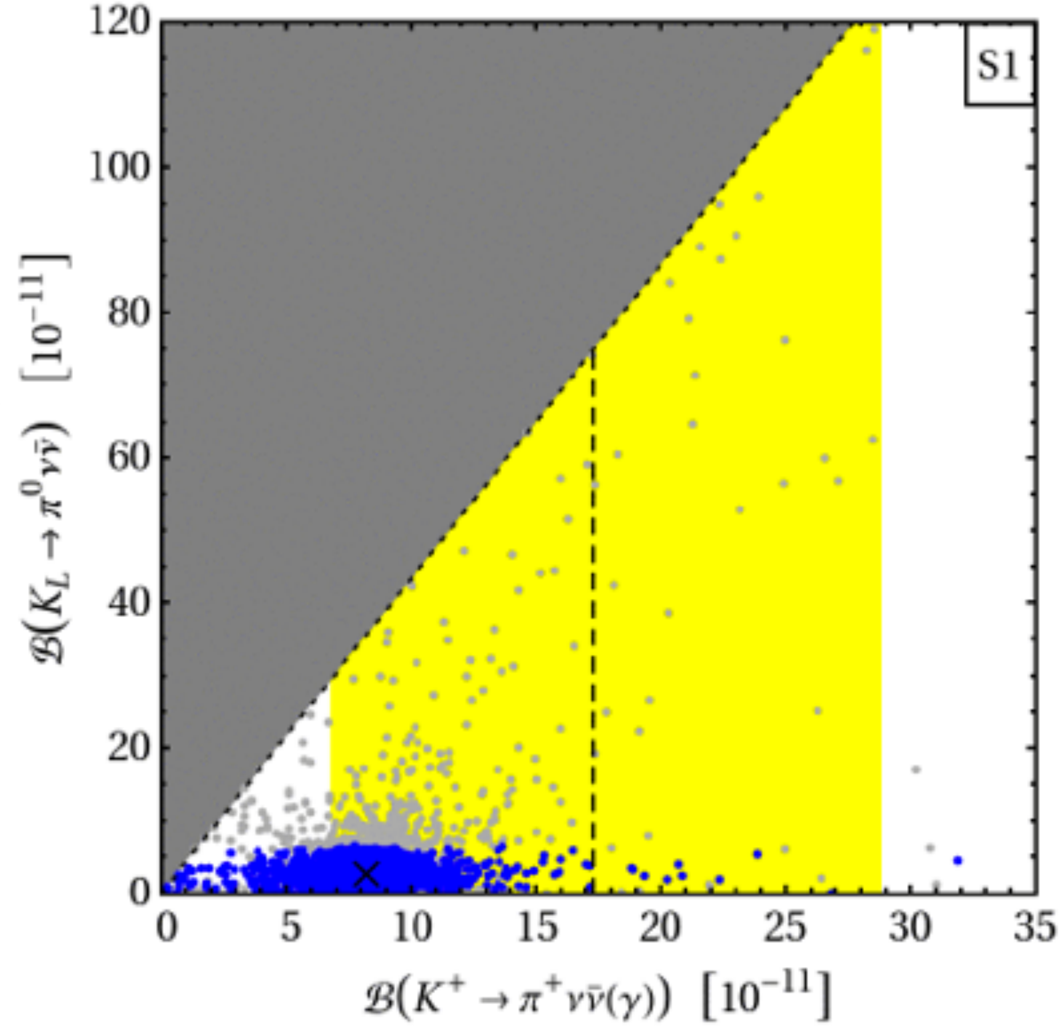
- Sizable effects in both golden modes possible



Without ε’ constraint



With ε’ constraint

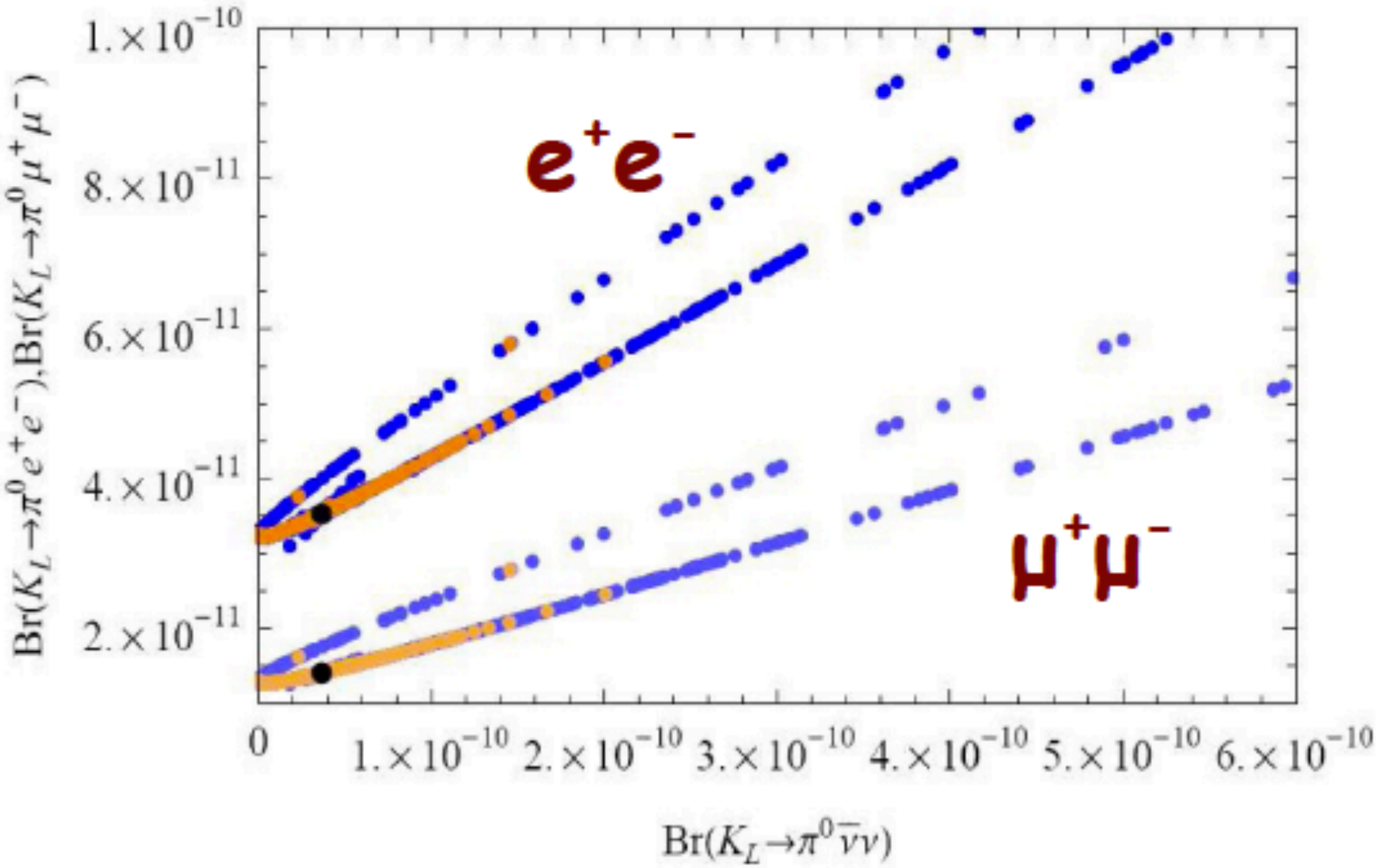


- ε’ constraint disfavors very large effects $K_L \to \pi^0 \nu\nu$: but 50% deviations from SM BR still possible

Bauer, Casagrande, Haisch, Neubert, 2009

- Correlations emerge among various BRs: falsifiable scenarios

Blanke, Buras, Duling, Gemmler, S.G., 2009



Result of the interplay of the coupling of Z with leptons & neutrinos

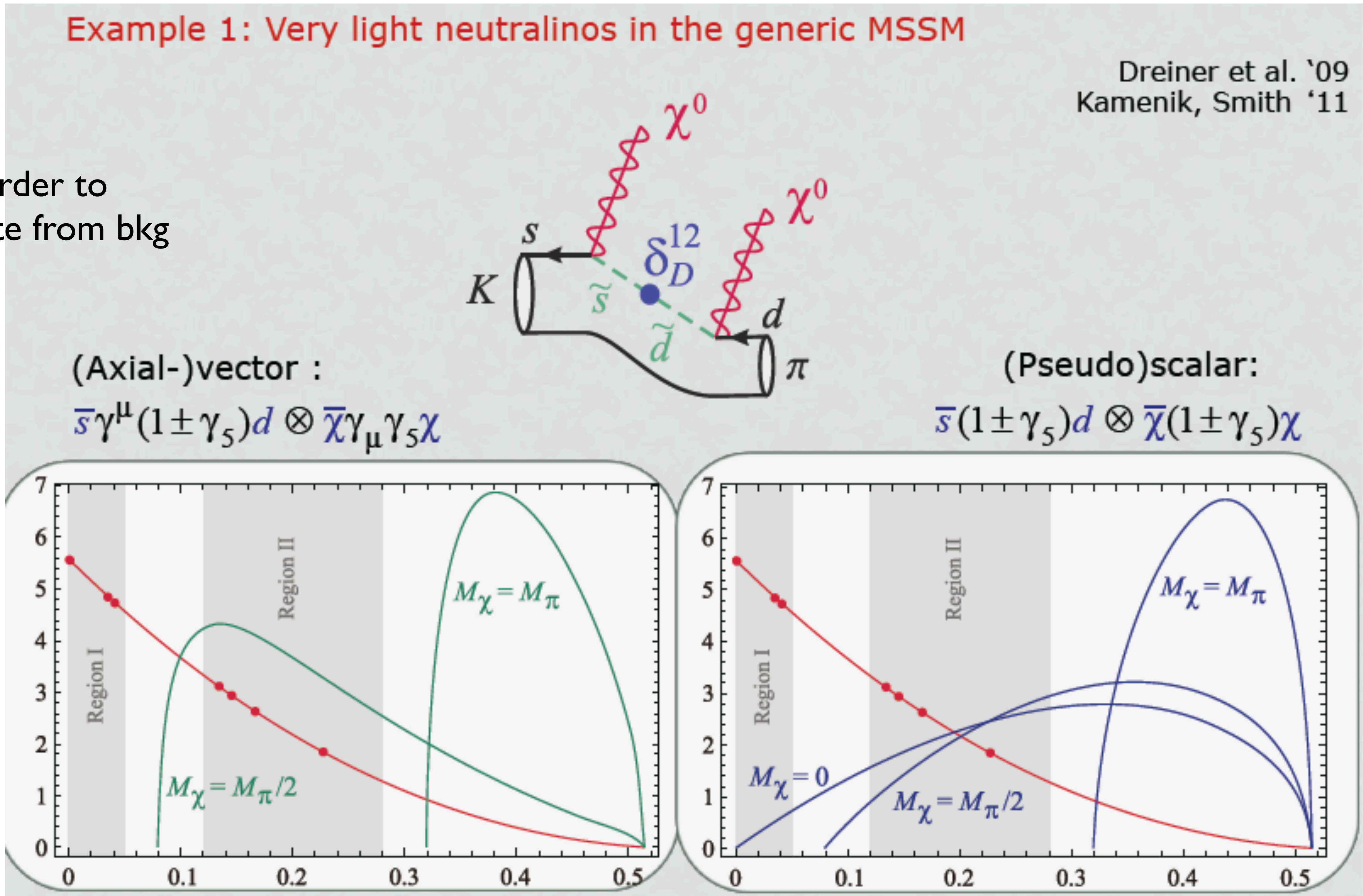
Measurement of both decays is a good test of the operator structure of the model

Philippe Mertens

The dark side of K→πνν

- Rare K decay can help constraining light weakly coupled particles

Harder to separate from bkg



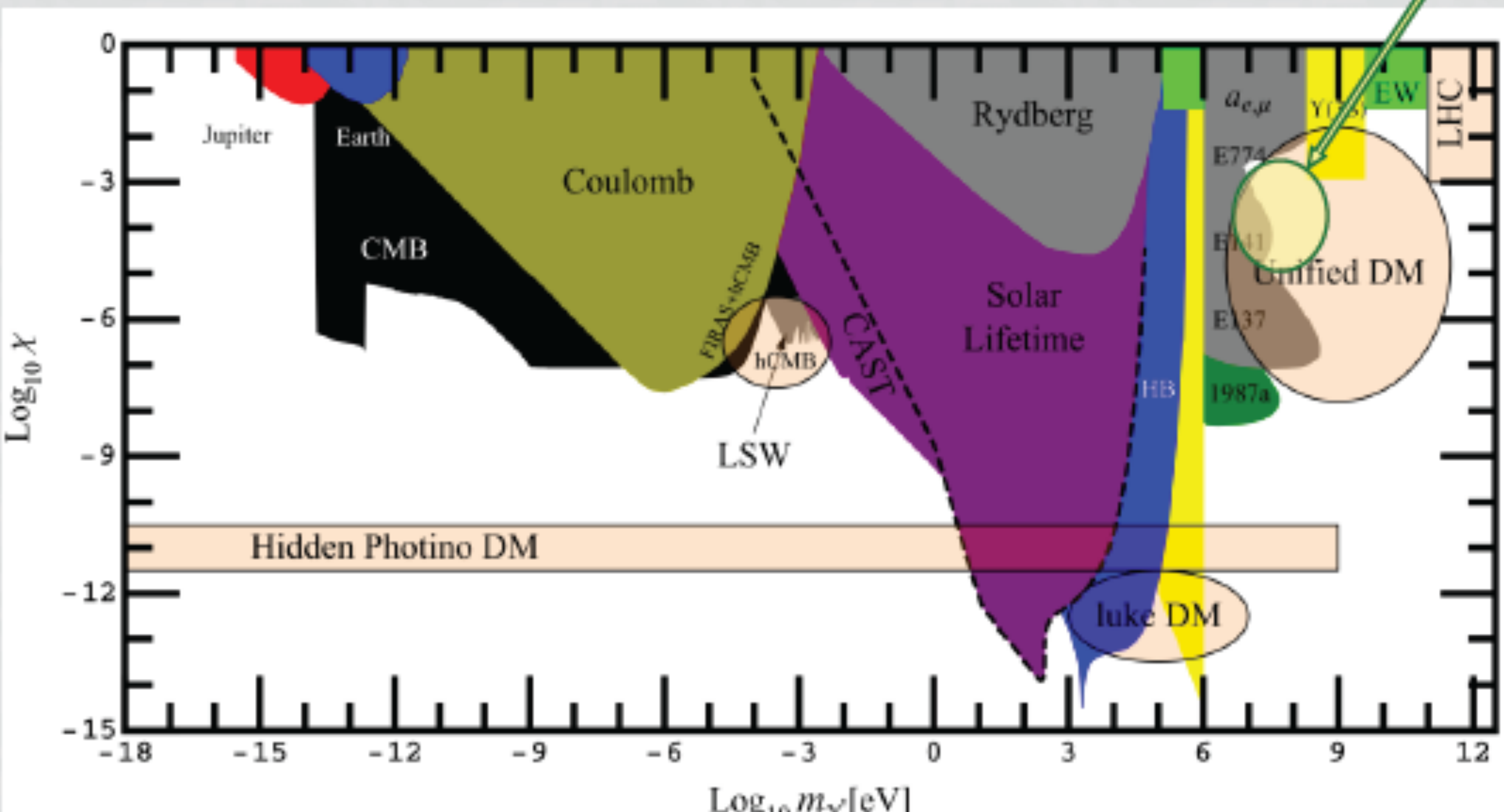
Philippe Mertens

Example 2: Kinetically-mixed light vector boson

Holdom '86
Arkani-Hamed et al. '08
Kamenik, Smith '11

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$

$K \to \gamma V$: A bound in the 10^{-12} range probes down to $\chi : 4 \cdot 10^{-5}$.

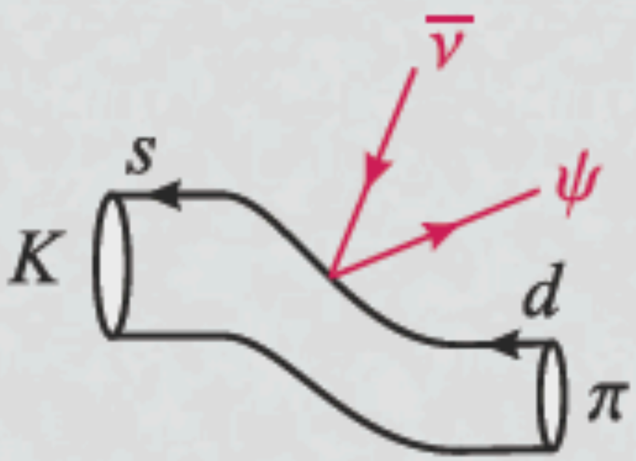


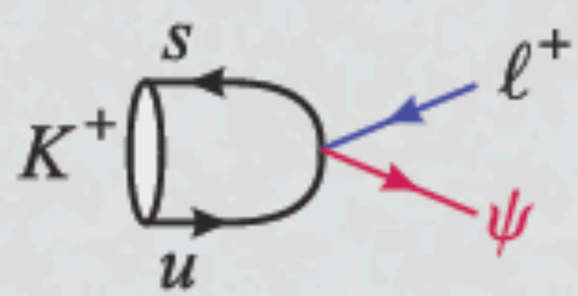
Jaeckel, Ringwald, 1002.0329

Example 3: Leptonic dark state (sterile neutrino,...)

Correlated neutral and charged current interactions:

$$\mathcal{H}_{eff} = \frac{1}{\Lambda^2}(\bar{d}_L s_R \otimes \bar{\nu}_L \psi + \bar{u}_L s_R \otimes \bar{\ell}_L \psi)$$





Rare FCNC modes
like $K \to \pi + \not{E}$ probe
scales up to $\Lambda :$ 100 TeV.

Current universality test,

$$\mathcal{R}_K^{\exp} = \frac{\Gamma(K_{e2})^{SM} + \Gamma(K \to e\psi)}{\Gamma(K_{\mu 2})^{SM} + \Gamma(K \to \mu\psi)}$$

reaches a similar scale $\Lambda :$ 80 TeV .

($\delta R_\pi^{\exp} : 10^{-3}$ would probe $\Lambda :$ 70 TeV)

Shrock ‘81; Gorbunov, Shaposhnikov ‘07; Kamenik, Smith ‘11

Example 3: Leptonic dark state (sterile neutrino,...)

Correlated neutral and charged current interactions:

- Hopefully this "summary of summaries" gives you the sense of the breadth of physics that can be accessed with rare and not-so-rare K decays
- What is the role of Project X?

like $K \to \pi + \not{E}$ probe scales up to $\Lambda \sim 100$ TeV.

$$\mathcal{R}_K^{\exp} = \frac{\Gamma(K_{e2})^{SM} + \Gamma(K \to e\psi)}{\Gamma(K_{\mu 2})^{SM} + \Gamma(K \to \mu\psi)}$$

reaches a similar scale $\Lambda \sim 80$ TeV.

($\delta R_\pi^{\exp} \sim 10^{-3}$ would probe $\Lambda \sim 70$ TeV)

Shrock '81; Gorbunov, Shaposhnikov '07; Kamenik, Smith '11

Rare K decays at Project X

- What modes can be measured
  - $K^+ \rightarrow \pi^+\nu\nu$: ORKA (MI) (start 2016) $\rightarrow$ Project X
  - $K_L \rightarrow \pi^0\nu\nu$: Project X phase I (start ~2020 ?) $\rightarrow$ ...
  - K_S / $K_L \rightarrow \pi^0 e^+ e^-$ interference (parasitic?)
  - Many other opportunities where ORKA detector can provide a substantial improvement

Process	Current	ORKA
$K^+ \to \pi^+\nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+\pi^0\nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+\pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+\gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+\nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+\nu_\mu\nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+\gamma\gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

D. Bryman

Benchmark sensitivities

(for golden modes)

- Lattice QCD (+ B decays) will reduce in 5-10 year the dominant parametric uncertainty: V_{cb} to <1%
- LQCD will also attack the l.d. contributions (hard)

Quantity	CKM	expt. now	lattice now	2014 lat.	2020 lat.	non-lattice method
f_K/f_π	V_{us}	0.2%	0.6%	0.3%	0.1%	-
$f_{K\pi}(0)$	V_{us}	0.2%	0.5%	0.2%	0.1%	1% (ChPT)
$B \to D^* \ell \nu$	V_{cb}	1.8%	1.8%	0.8%	$< 0.5\%$	$< 2\%$ (Incl. $b \to c$)
$B \to D \ell \nu$	V_{cb}	4%	2%	$< 2\%$	$< 0.5\%$	$< 2\%$ (Incl. $b \to c$)

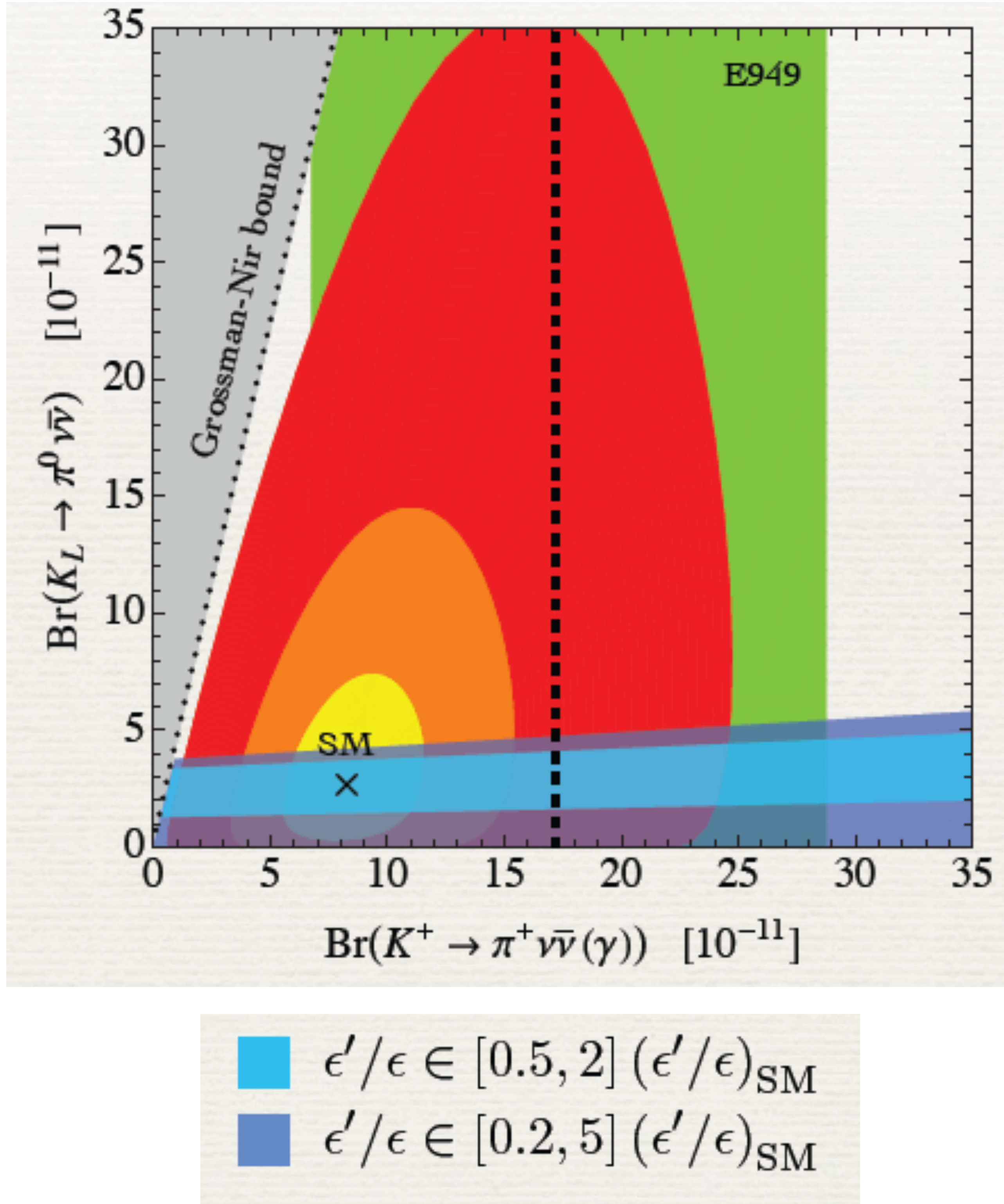
J. Laiho, LQCD WG

- By 2020: $BR_{Th}(K^+ \to \pi^+ \nu\nu)$ @ 5% and $BR_{Th}(K_L \to \pi^0 \nu\nu)$ @ 5%
- These figures should be the target for Project X experiments (by then NA62 will have ~10% measurement, KOTO few events)

- With this target precision retain "discovery potential" even in presence of the ε' constraint

- This target precision makes Project X searches of $K_L \to \pi^0\nu\nu$ with O(10) events not so exciting as a final goal, but only as a stepping stone

- 5% BR will be interesting anyways in 2025: it will either be measuring the flavor sector of something seen at the LHC or it will be an attempt to find a crack in the SM



Extra Slides

$K \to \pi \nu \bar{\nu}$ Prospects

$K^+ \to \pi^+ \nu \bar{\nu}$

Now: $B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \, x10^{-10}$

(7 events)

Future: Sensitivity at SM $7.8 \, x10^{-11}$

Goals	NA62 CERN	ORKA FNAL MI	Proj.X
Events/ yr	40	200	340
S/N	5	5	5
Precision	10%	5%	3%

$K_L^0 \to \pi^0 \nu \bar{\nu}$

Now: $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 2.6 \, x10^{-8}$

Future: Sensitivity at SM $2.4 \, x10^{-11}$

Goals	KOTO * J-PARC	Proj.X
Events/yr	~1	"200"
S/N	~1	5-10
Precision		5%

* J-PARC plans a phase II to reach higher sensitivity.

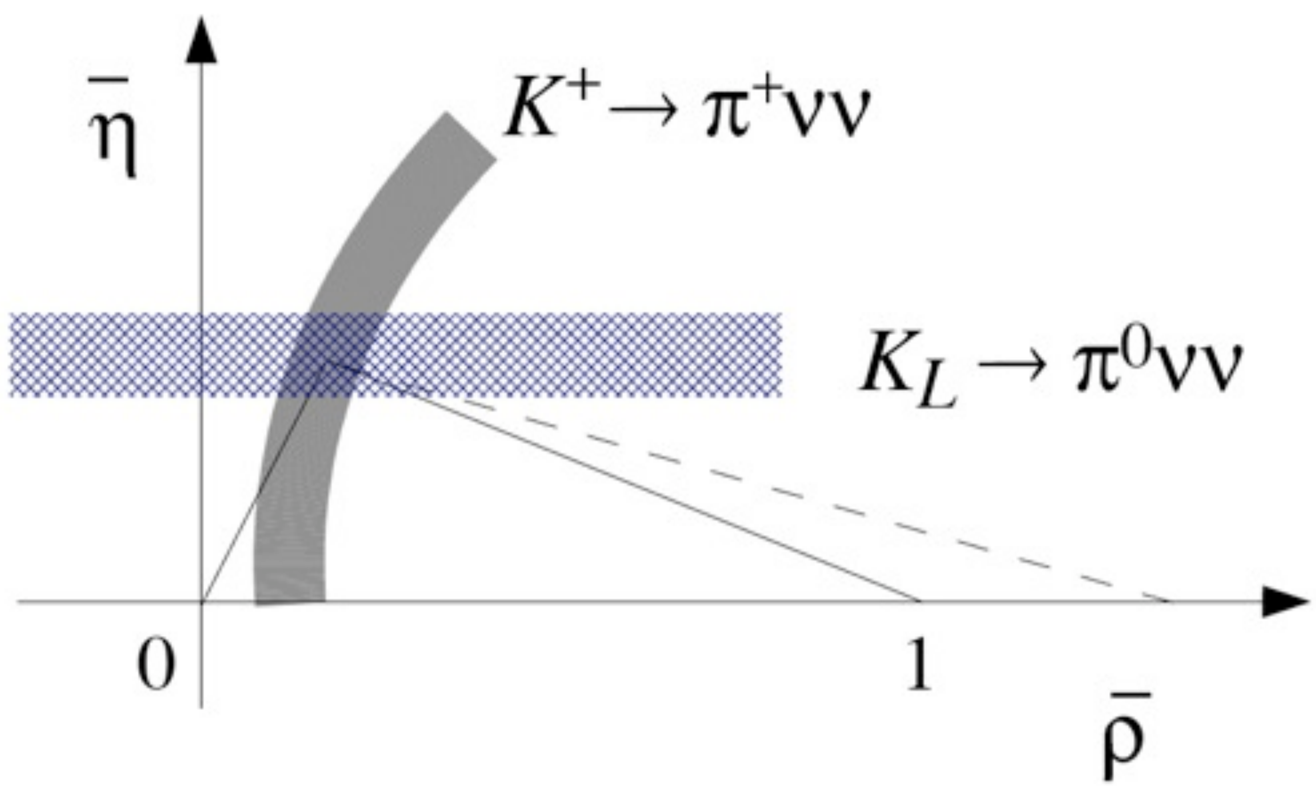
Parametric uncertainties

- More on parametric uncertainties in Br($K_L \to \pi^0 \nu\nu$) A. Kronfeld
- Using CKM unitarity and dropping $|V_{tb}| - 1$:

$$\frac{\mathrm{Im}\, V_{ts}^* V_{td}}{|V_{us}|} = -\frac{|V_{cb}|\,\mathrm{Im}\, V_{ub}}{|V_{us}|} = \frac{|V_{cb}||V_{ub}|\sin\delta_{KM}}{|V_{us}|} = \frac{(A\lambda^2)(A\lambda^3\eta)}{\lambda}$$

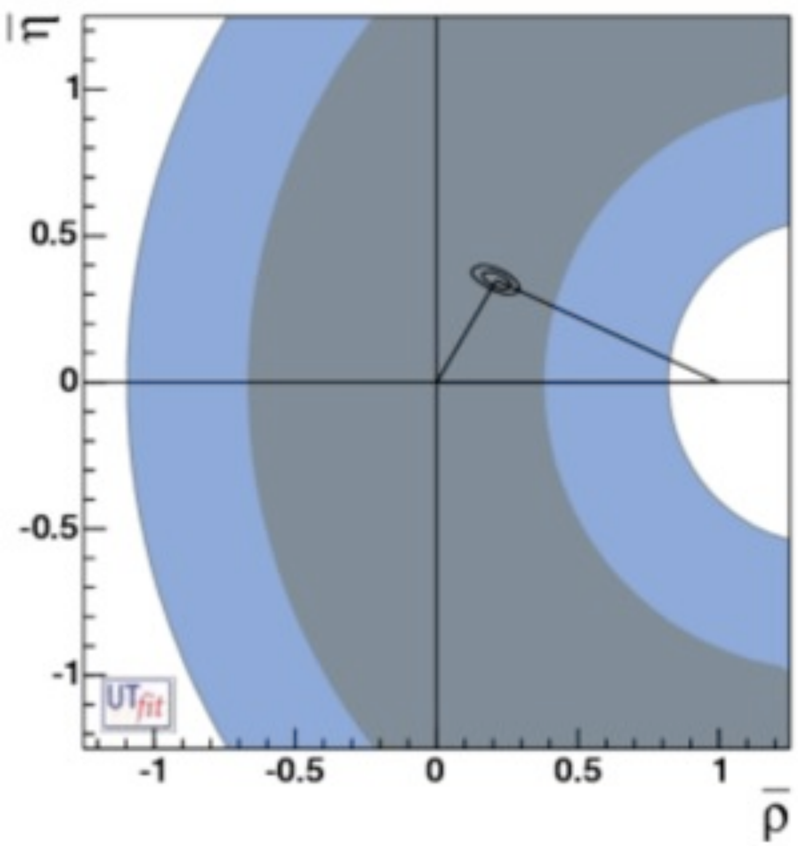
- In the next decade (to be safe), parametric uncertainty on BR will go down to ~4-5%
  - V_{us} @ 0.5%, V_{cb} @ 0.5% (exclusive + LQCD)
  - V_{ub} @ 2% (superB + LQCD)
  - sin δ_{KM} @ 1% -> 0.5% (LHCb)

	SM	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}$	$7.81(75)(29) \times 10^{-11}$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ E787 E949
$K_L \to \pi^0 \nu\bar{\nu}$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a
$K_L \to \pi^0 e^+ e^-$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 28 \times 10^{-11}$ KTEV
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 38 \times 10^{-11}$ KTEV

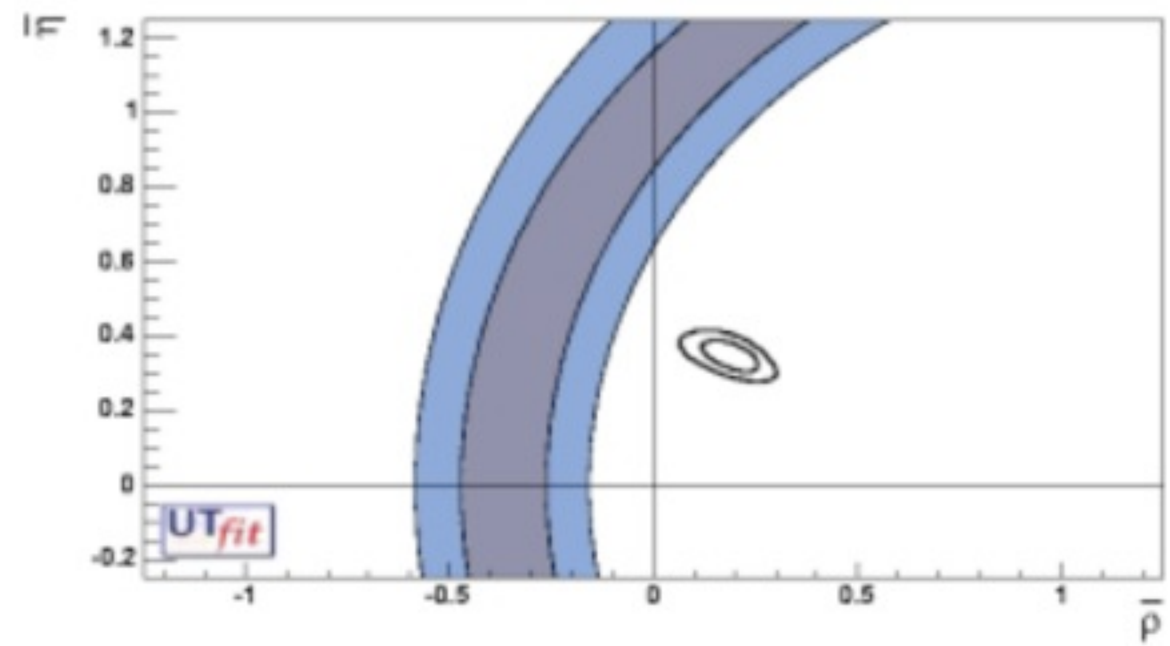


- "Discovery potential": disagreement with SM prediction would signal BSM effects
- Example: $K^+ \rightarrow \pi^+ \nu\nu$ (graphical representation)

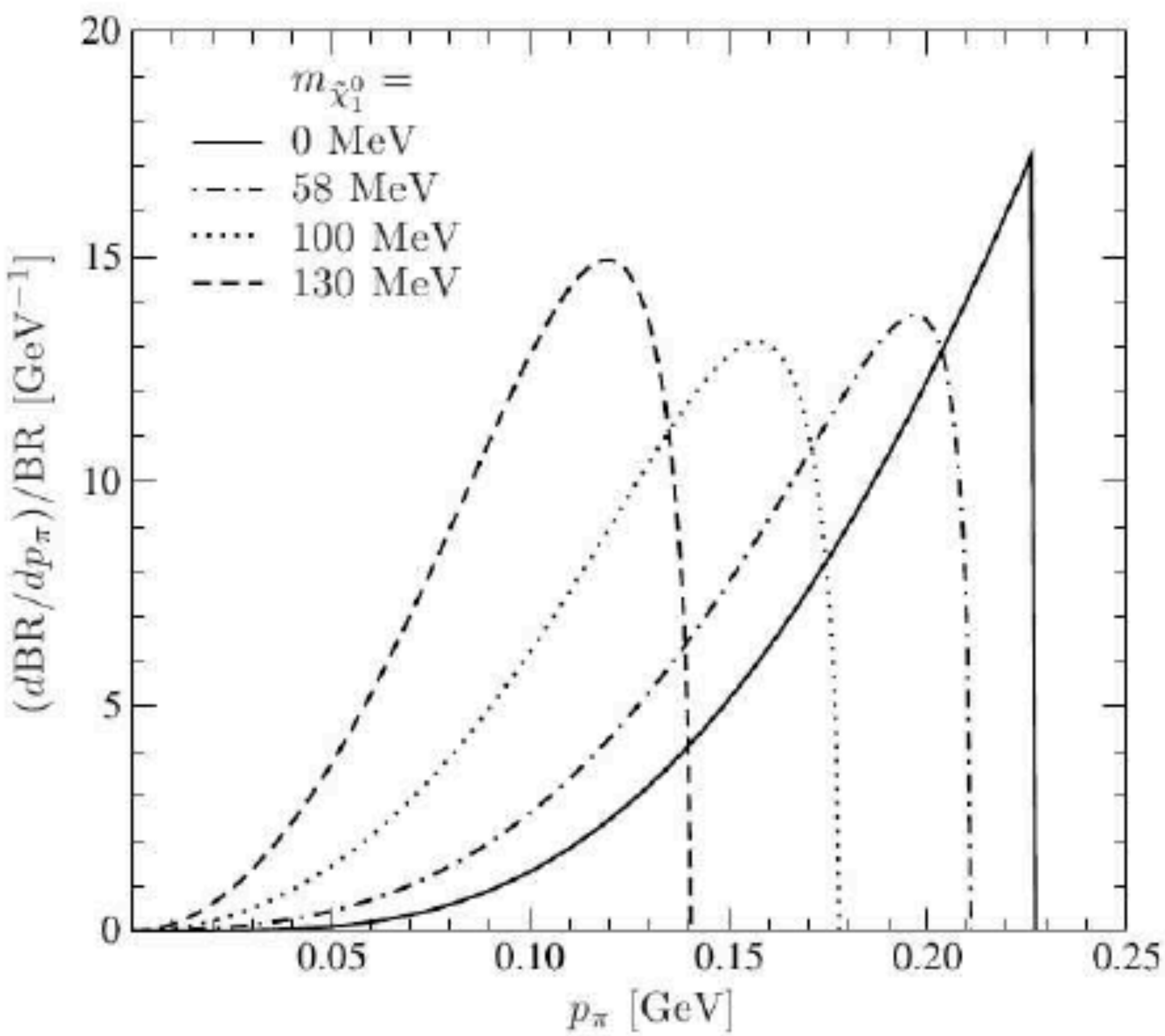
Current situation



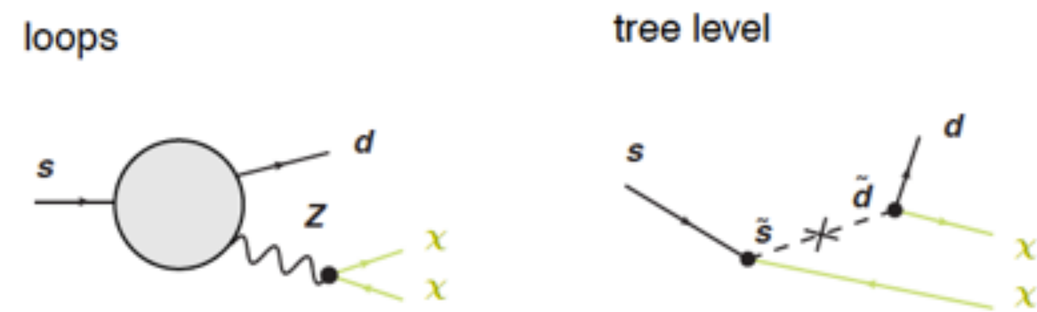
Same central value with 10% uncertainty and 1/2 theory error



- If neutralinos are very light, the $K \to \pi\chi\chi$ decay is possible and can lead to a non-standard p_π spectrum.



Dreiner et al. Phys. Rev. D80 (2009)



- the p_π spectrum for $K \to \pi\chi\chi$ depends on the mass of the neutralinos
- more difficult to separate from backgrounds